Exhibit 17

Thyristor devices. Courtesy of the General Electric Company, Semiconductor Products Dept., Auburn, N.Y.

SEMICONDUCTOR POWER DEVICES

PHYSICS OF OPERATION AND FABRICATION TECHNOLOGY

SORAB K. GHANDHI
Rensselaer Polytechnic Institute

A WILEY-INTERSCIENCE PUBLICATION
JOHN WILEY & SONS, New York • London • Sydney • Toronto

Library of Congress Cataloging in Publication Data:

Ghandhi, Sorab Khushro, 1928-
Semiconductor power devices.

"A Wiley-Interscience publication."
Includes bibliographical references and index.
1. Power semiconductors. I. Title.

TK7871.85.G43 621.31'7 77-8019
ISBN 0-471-02999-8

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

A plot of this relationship also appears in Fig. 2.16. Note that for the same radius of curvature, the spherical junction has an even lower breakdown voltage than the cylindrical junction.

Extremely small radii of curvature are encountered in sharp corner regions associated with masked diffusion through rectangular windows. Such corners must always be avoided by rounding them off; often designers of power devices use circular lateral geometry to avoid completely junction breakdown due to spherical curvature.

2.5.3 Diffused Guard Ring Structures

The diffused guard ring can be used to force the curvature of the depletion layer into the shape shown in Fig. 2.13*a*. The avalanche photodiode provides an excellent example for this scheme, since it allows the use of a shallow diffusion (for efficient photodetection) while avoiding edge breakdown resulting from its sharp curvature.

Figure 2.17 shows an n^+-p structure of this type, which is made by first diffusing a deep n^+-type annular ring, followed by a shallow n^+-circular diffusion. The deep annular diffusion is designed to have a breakdown voltage at its edges that is higher than the BV of the shallow diffusion in its parallel plane region. This can be readily achieved, since the guard ring has a smaller grade constant $\mathscr{a}$ than the shallow n^+-diffusion.

Note that the depletion layer edge of the shallow junction now curves away from the n^+-region. This means that breakdown will occur over the parallel plane section, and uniform avalanching can be achieved.

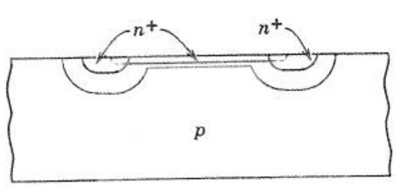

Fig. 2.17 Diffused guard ring structure.

Diffused guard rings can also be incorporated [19] into punched-through structures to limit the field due to depletion layer curvature. To accomplish this, the device is fabricated in the form of a circular p^+-n structure as in Fig. 2.18, with a series of appropriately spaced concentric p^+-ring diffusions. These rings are left floating and are free to adopt any potential during device operation.

The depletion layer is initially associated with the main junction P_0, and extends outward with increasing reverse bias. The spacing between P_0 and

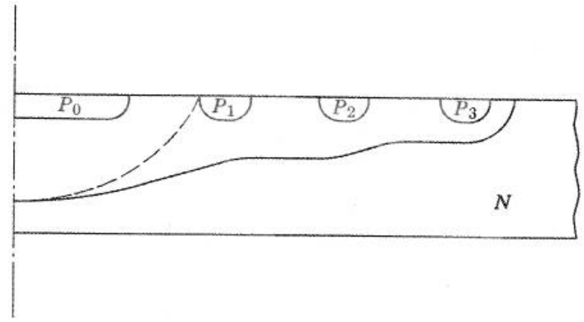

Fig. 2.18 Diffused field-limiting rings.

P_1 is such that punchthrough occurs *before* the avalanche breakdown voltage of the cylindrical junction associated with P_0. Thus the maximum $\mathcal{E}$ field across the main junction P_0 is limited; any further increase in reverse voltage is taken up by P_1 until the depletion layer punches through to P_2, and so on. Ultimately, the device breaks down at the cylindrical junction associated with the last diffused ring.

Consider, in the limit, identically spaced guard rings whose diffusion depth is very large compared to the main diffusion. If BV_{PT} is the punchthrough voltage associated with each spacing, and BV_{CY} is the breakdown voltage of the cylindrical junction associated with the nth guard ring, the breakdown voltage of the device is given by

$$BV \cong nBV_{PT} + BV_{CY} \tag{2.71}$$

In addition, the voltage adopted by each guard ring varies linearly with the voltage on the main junction, once punchthrough occurs.

At the other extreme, consider extremely shallow guard rings of infinitely small width. These have no effect on the behavior of the main junction and serve only as probes on the depletion layer. For large ring diameters, it can be shown from geometric considerations that the voltage adopted by these rings will vary approximately as the square root of the voltage on the main junction, once punchthrough occurs.

For reasons of economy, it is desirable to have all junctions made in a single diffusion step; this ensures that the practical guard ring structure will fall between the two extremes just described. Furthermore, structures are most commonly limited to a single guard ring to avoid excessively large area. Computer-aided studies of such devices [20] have shown that once punchthrough occurs, the voltage adopted by the guard ring varies as the 0.65th power of the applied reverse voltage.

Figure 2.19 shows the fraction of the parallel plane breakdown voltage (BV_{PP}) that can be achieved by a curved junction having one guard ring,

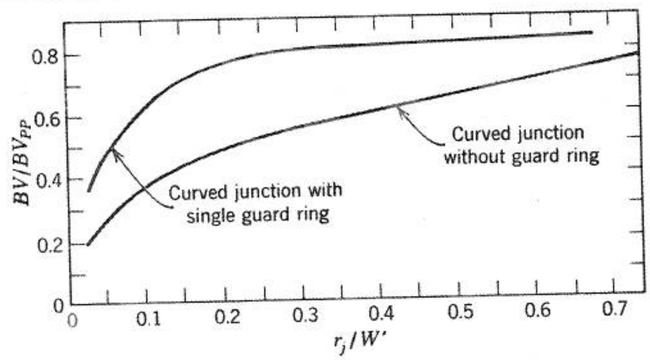

Fig. 2.19 Breakdown voltage of a field-limiting ring structure. Copyright © 1975 by the Institute of Electrical and Electronics Engineers, Inc. Reprinted with permission from Adler et al. [20].

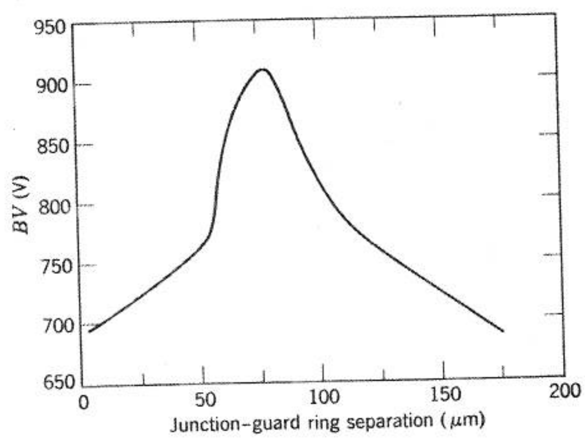

Fig. 2.20 The effect of ring placement. Copyright © 1975 by the Institute of Electrical and Electronics Engineers, Inc. Reprinted with permission from Adler et al. [20].

as a function of r_j/W', where r_j is the radius of curvature of the junction, and W' is the breakdown depletion layer width of a parallel plane device built on the same starting material. For the purpose of comparison, results for a curved junction *without* a guard ring are also shown. Inspection of this figure indicates that the guard ring can improve the breakdown voltage by as much as 80% for small radii of curvature* (i.e., for low

*From (2.71) it is seen that even for the ideal case, a single guard ring cannot achieve a 2:1 improvement in breakdown voltage over the junction with no guard ring.

voltage diodes as well as high voltage transistors). However this improvement falls off to only 10% for high voltage diodes, which usually have larger values of r_j/W'.

The breakdown voltage of the guard ring structure has also been shown to be a relatively sensitive function of the separation between the main junction and the guard ring, so that the data of Fig. 2.19 hold only for an optimally spaced structure. The sensitivity to this separation for a typical device is indicated in Fig. 2.20. Thus ring placement must be reasonably precise if full advantage is to be taken of this technique.

2.5.4 Field Plate Structures

The field plate provides an alternate means for control of the depletion layer edge near the surface of a semiconductor, and it is particularly convenient for use with diffused junctions made by photomasking processes. In practice, the field plate is placed on top of the oxide covering the junction and biased with respect to the semiconductor beneath it. As a consequence of charge neutrality, the charge on this plate is balanced by the formation of a space charge layer of opposite polarity type in the semiconductor bulk. Thus positive charges on the plate induce negative charges in the underlying semiconductor, making it more n-type at the surface. In like manner, negative charges on the plate make the underlying semiconductor more p-type. This effective change in conductivity may be used to control the curvature of the depletion layer edge, hence its breakdown voltage, in the region near the surface.

Consider an n^+-p diode like that in Fig. 2.21. Here a field plate is placed on an oxide that is assumed to be ideal and charge-free, and biased with respect to the p-region. The depletion layer edge, for zero voltage (hence zero charge) on the field plate is labeled 0 in this figure. The application to the field plate of negative voltage of successively increasing magnitude, results in the p-region becoming successively more p-type and the depletion layer becoming more tightly curved, as shown by $0, 1, 2$. Thus the BV is reduced from its original value.

In like manner, the application of successively increasing positive voltage on the field plate V_{FP} (hence more positive charge) results in the p-region becoming successively less p-type, thus acquiring increased surface resistivity. The resulting changes in depletion layer edge are labeled $0, 1', 2', 3'$. With each increase in V_{FP}, the curvature is further reduced, resulting in an increased breakdown voltage, approaching that for the parallel plane junction.

If BV volts is applied to the n^+-region (see Fig. 2.21) and V_{FP} to the field plate, the net voltage across the oxide is $BV - V_{FP}$, in the region over

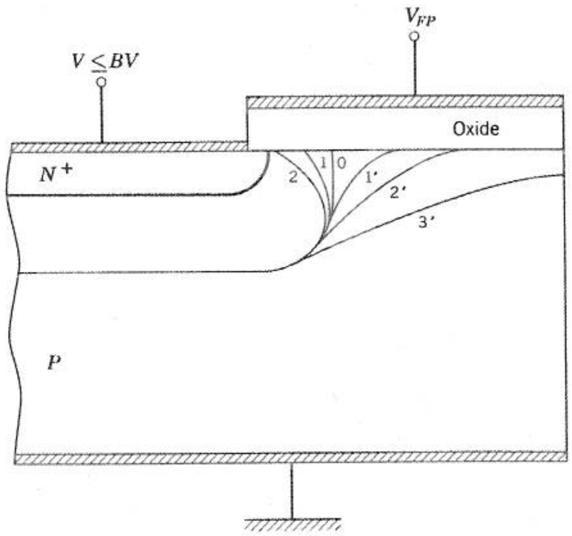

Fig. 2.21 The effect of a field plate on the depletion layer.

the n^+-region. With a thin oxide (relative to the depletion layer width), the maximum $\mathcal{E}$ field concentration occurs in this region. As a result, we can expect, to a crude approximation, that breakdown will occur at a constant value of $BV - V_{FP}$. Thus the breakdown voltage of the junction should be related to the voltage on the field plate by

$$BV \cong V_{FP} + \text{const} \tag{2.72}$$

until the parallel plane breakdown voltage is reached. This has been experimentally observed [21] over wide ranges of values of V_{FP}.

In the foregoing arguments it has been assumed that conductivity changes in the n^+-layer are negligible. In addition, the positive charge applied to the field plate was in all cases insufficient to invert the underlying p-region to n-type. Although it is possible for both these conditions to be violated, values of V_{FP} can be chosen to ensure that this does not happen.

The effect of built-in charges in the oxide is comparable to putting a fixed bias on the field plate. Thermally grown oxides typically have about 10^{11} positive charges per square centimeter. For a 1μm thick oxide, this results in an effective bias of about $+5$ V on the field plate, which can be ignored for all practical purposes.

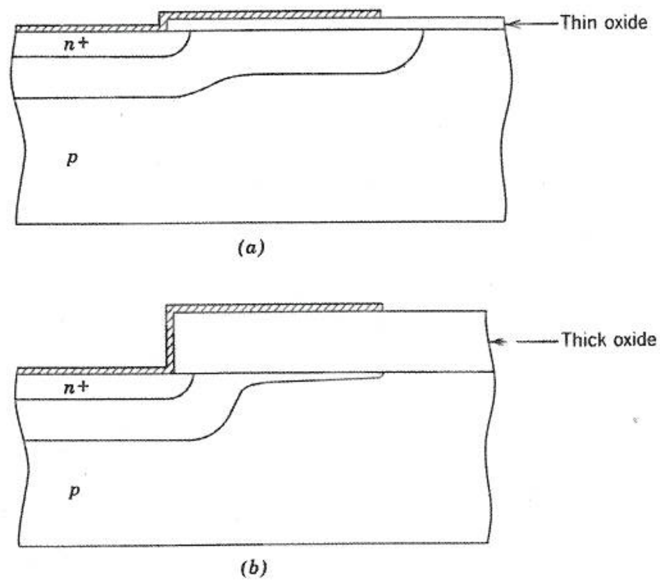

Fig. 2.22 Thin and thick oxides.

In practice, a separate gate voltage supply is avoided by tying the field plate to one region of the junction, (Fig. 2.22*a*). Here, consider an extreme case of a thin oxide on a high voltage junction. By way of example, assume a 1 μm oxide and a 100 V junction. The depletion layer width for this junction is about 100 μm, resulting in an average electric field of 10 V/μm in the semiconductor. Since the relative permittivity of silicon dioxide is about 4, whereas that for silicon is 12, the average field in the oxide will be about 30 V/μm. Consequently the depletion layer supports 1000 V in the region below the n^+-diffusion and 970 V in the region covered by the field plate. Thus its width is approximately constant right out to the field plate edge, as shown. All the field concentration region is now out *beyond* the edge of the field plate, and avalanche multiplication preceding breakdown is initiated in this edge region. In addition, since the depletion layer curvature is essentially unchanged, the breakdown voltage is close to that obtained with no field plate and is undesirably sensitive to the effects of extraneous charge migration on the oxide surface.

Figure 2.22*b* shows the other extreme of a field plate on a very thick oxide, say 30 μm.* Again, assume that the voltage supported by the region

*Grown oxides are usually limited to about 1–2 μm thickness before cracking due to differential thermal expansion effects. However pyrolytic oxides and low temperature glasses can be readily deposited in this thickness range.

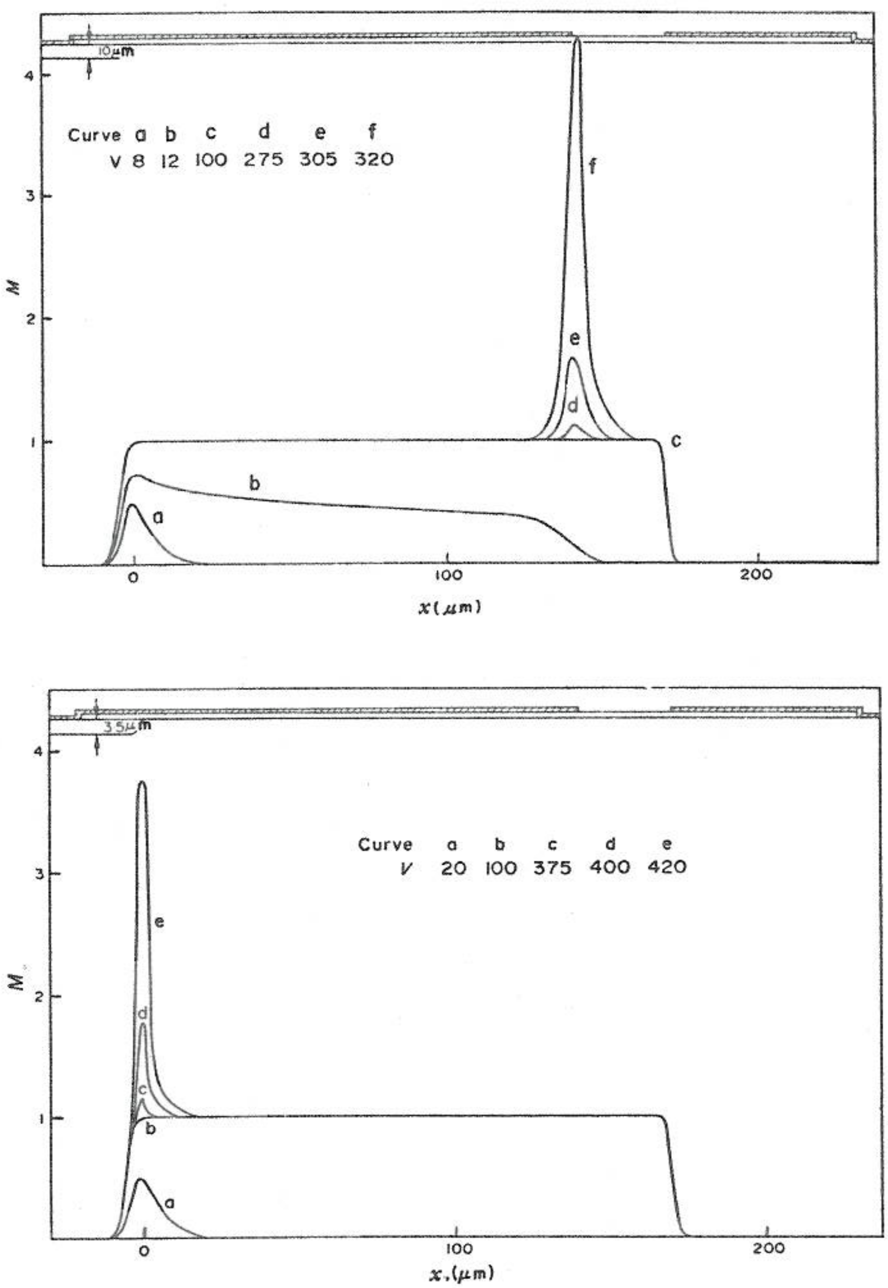

Fig. 2.23 Multiplication in thin and thick oxide field plate structures. Copyright © 1972 by *Solid State Electronics*. Reprinted with permission from Conti and Conti [22].

under the diffusion is 1000 V and that the electric field in the oxide is 30 V/μm. Now, however, 900 V is supported by the depletion layer in the region below the n^+-diffusion, and only 100 V in the region covered by the field plate; thus edge breakdown is eliminated. Yet since the depletion layer curvature near the metallurgical junction is virtually the same as that for no field plate, breakdown occurs in this region at about the same voltage as for a cylindrical junction without a field plate. The field plate is thus ineffective for either extreme situation.

Avalanche multiplication in field plate structures with thin and thick oxides is dramatically illustrated in the experimental data [22] of Fig. 2.23*a* and 2.23*b*, respectively. Transparent electrodes were used, and the multiplication factor was determined by measuring the optical emission associated with hole-electron pair recombination in the depletion layer. Figure 2.23*a* depicts a device with a thin oxide (0.5 μm), that avalanches at the edge of the field plate. The thick oxide (2 μm) structure of Fig. 2.23*b* is seen to avalanche internally, near the diffused junction boundary. Furthermore, the thin oxide structure has a diffusion depth of 10 μm and a background resistivity of 32 ohm-cm, and it breaks down at 320 V. On the other hand, the thick oxide device has a shallow diffusion (3.5 μm) and a low background resistivity (12 ohm-cm) but breaks down at a somewhat higher voltage (420 V). Thus although neither of these designs is very effective, it is preferable to have avalanching occur near the diffusion edge than at the edge of the field plate.

The ideal field plate structure requires the use of an oxide that is very thin near the diffusion window and thickens outward from the metallurgical junction region. Tapered oxides of this type are not achievable by simple technological means; however stepped oxides have been used to approximate this taper. For example, planar p^+-n diodes with breakdown voltages as high as 900 V have been made [22] with 10 μm diffusion depth, 0.6 μm stepped to 3 μm oxide thickness, and $10^{14}/\text{cm}^3$ background concentration. The theoretical value of BV for cylindrical junctions of this type is 500 V without a field plate, whereas the value for the parallel plane junction with the same background concentration is 1400 V. Thus the use of a field plate can result in a significant improvement in breakdown voltage over the circular junction.

2.5.5 Equipotential Rings

Investigations have shown that junctions with field plates often exhibit slowly drifting breakdown characteristics. Much of this problem can be traced to the fact that the oxide has a finite conductivity, so that any charge on the field plate slowly extends out over the surrounding oxide. If

with an attendant increase in soft spot formation. Given these advantages, it is highly probable that electron irradiation will be increasingly adopted for the manufacture of fast recovery thyristors.

6.4 OHMIC CONTACTS

In addition to excellent mechanical properties, an ohmic contact must have low electrical resistance and an essentially linear voltage-current characteristic. Furthermore, it must serve purely as a means for getting current into and out of the semiconductor while playing no part in the active processes occurring within the device.

An ohmic contact can readily be achieved to a heavily doped, degenerate semiconductor, since this material has an extremely short minority carrier lifetime. Thus a good, strong mechanical connection is the principal consideration when making such a contact. Regions of this type are often directly attached to the leads, or to the case to which the circuit connection is to be made.

An ohmic contact to a lightly doped semiconductor is accomplished by forming an n^+-contact to an n-type region or a p^+-contact to a p-type region. These high-low junctions [35], of the n^+-n or p^+-p type, have extremely high leakage currents that completely mask the usual diode-like behavior. Here their voltage-current characteristics approximate a straight line going through the origin and are essentially "ohmic."

Techniques for junction formation described in Section 6.2 can also be used for the fabrication of ohmic contacts. A few examples follow.

1. The diffusion of an n^+-region into the n-collector of a microcircuit transistor (Fig. 6.15*a*), followed by a p^+-alloyed interconnection layer of aluminum. This combination results in an n-n^+ junction followed by an n^+-p^+ junction in series with it.
2. The alloying of an aluminum p^+-region to the p-gate region of a thyristor (Fig. 6.15*b*).
3. The alloying of an aluminum p^+-region to the p-anode region of a thyristor, to form a p^+-p contact (Fig. 6.15*b*).
4. The epitaxial growth of an n-collector region to an n^+-subtrate, as shown in Fig. 6.15*c* for a transistor. Here the n^+-region provides for ohmic contact to the n-collector, even though the latter is epitaxially grown on the former.